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GRADIENTS OF GALACTIC COSMIC RAYS AND ANOMALOUS COMPONENTS

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ABSTRACT

Measurements of radial and latitudinal gradients of galactic cosmic rays and anomalous components now cover radii from 0.3 to 40 AU from the sun and latitudes up to 30° above the ecliptic plane for particle energies from ~10 MeV/n up to relativistic energies. The most accurate measurements cover the period 1972-1987, which includes more than one full 11 year cycle of solar activity. Radial gradients for galactic cosmic rays of all energies and species are small ($\lesssim$ 10%/AU), and variable in time, reaching a minimum of near 0%/AU out to 30 AU for some species at solar maximum. Gradients for anomalous components are larger, of order 15%/AU, may show similar time variability, and are relatively independent of particle species and energy. Latitude gradients have only recently been measured unambiguously by the Voyager 1 and 2 spacecraft. For the period 1985-86 the intensity decreased away from the ecliptic for all species and energies. For galactic cosmic rays, the measured gradients are ~0.5%/degree near 20 AU, while for anomalous components the gradients are larger, ranging from 3-6%/degree. Comparison with a similar measurement for anomalous helium in 1975-76 suggests that the latitude gradients for anomalous components have changed sign between 1975 and 1985. For galactic cosmic rays, the available evidence suggests no change in sign of the latitudinal gradient for relativistic particles.

INTRODUCTION

After many years of measurements by sensors on the ground, in high altitude balloons, and on spacecraft, the cosmic radiation environment of the earth is well characterized (e.g. Adams, 1986). At low energies ($\lesssim$ few GeV) the cosmic ray intensity observed at earth is much lower than that which exists in the interstellar medium. The intensity reduction is a result of the process of solar modulation, which is caused by the interaction of cosmic rays with the interplanetary magnetic fields carried outward from the sun by the solar wind. The modulated intensity is determined by a balance between inward diffusion of the cosmic rays through the irregular interplanetary magnetic fields, gradient and curvature drifts as a result of the non-uniform nature of the fields, outward convection by the solar wind, and cooling, or adiabatic deceleration, of the cosmic ray gas as a result of its coupling to the diverging solar wind (see, for example, Quenby, 1984). Above a few GeV/nucleon the effects of modulation on the intensity are small, but cosmic rays with interstellar energies below a few hundred MeV/nucleon are effectively excluded from the inner heliosphere by modulation. As seen from Figure 1, which shows the intensity of relativistic cosmic rays as measured by the Climax neutron monitor and the monthly sunspot number, the cosmic ray intensity in the heliosphere is highest at the minimum of the 11-year solar activity cycle. However, observations from 1 to near 40 AU in near-solar-minimum conditions show that even at solar minimum the intensity at low energies is strongly affected by modulation.

As a result of the modulation, we have very little reliable information concerning the interstellar intensities and spectra of galactic cosmic rays at energies below ~1 GeV/nucleon.

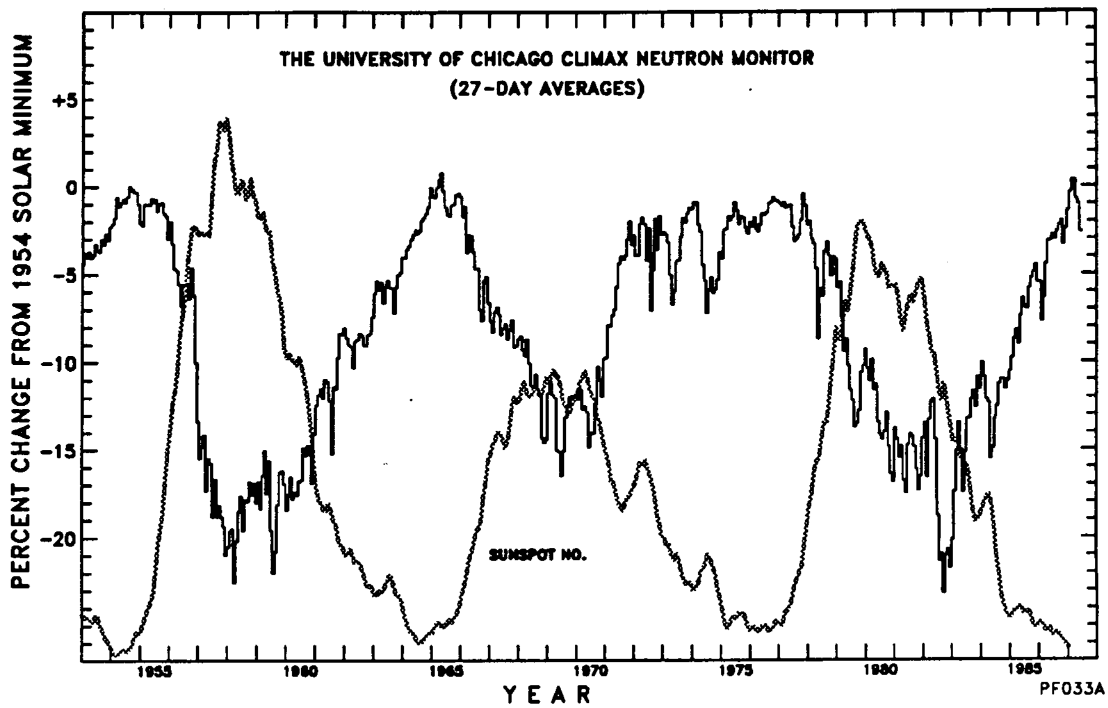

Figure 1. Monthly average Climax neutron monitor counting rate and smoothed sunspot number.

Such information as does exist is based on comparison of the modulated electron spectrum observed at 1 AU with the interstellar electron spectrum deduced from analysis of radio observations of synchrotron emission in the galactic magnetic field. Such a comparison makes it possible to deduce the strength of the modulation and, given a model for the modulation process, to "demodulate" the observed nucleonic cosmic ray spectrum. For example, Evenson et al. (1983) have found that an interstellar proton spectrum of the form

$$\frac{dJ}{dE} = 3.73 \times 10^9 [T + 1335 - 835\exp(-T/1000)]^{-2.75} \quad (\mathrm{s\ m^2\ sr\ MeV/n})^{-1} \tag{1}$$

provides a satisfactory fit to observed modulated intensities when used with a quasi-steady, spherically symmetric model of modulation. The analysis does not lead to a unique form for the interstellar spectrum, however. For example, Figure 2 , compiled by Garcia-Munoz, Pyle, and Simpson (private communication, 1987), shows three different interstellar proton and helium spectra that have recently been proposed as consistent with modulated spectra at 1 AU. Partly because of this uncertainty, we cannot now deduce accurately either the location of the boundary or the intensity at the boundary for particle energies $\lesssim 1$ GeV.

As part of an experimental program to determine the mechanisms of modulation and the physical scale of the modulation region, measurement of radial and latitudinal gradients of galactic cosmic rays has been a principal activity of experimental cosmic ray physics since the first spacecraft left the orbit of earth. By far the most productive period for such measurements has been the period from the launch of Pioneer 10 in 1972 until the present. In this period, various spacecraft have explored the heliosphere over a radial range from the orbit of Mercury to ~40 AU from the sun, and over a latitude range from near the ecliptic to ~30° north latitude. Figure 3 shows ecliptic projections of the trajectories of the Voyager and Pioneer spacecraft, which have performed the most extensive exploration of the heliosphere. Whereas before these missions estimates of the radius of the modulation region in the heliosphere had been in the neighborhood of 10 AU, current estimates range from ~ 50 AU to more than 100 AU.

The goal of this paper is to summarize what we currently know concerning the spatial and temporal variations of the galactic cosmic ray intensity and of the anomalous components, which are nuclei of He, N, O, and Ne, (and, more recently reported, of C and Ar (Cummings and Stone, 1987)) observed at energies $\lesssim$100 MeV/nucleon and believed to be accelerated in the outer regions of the heliosphere. While I have tried to represent fairly the results of all current work, as this workshop was intended primarily to provide guidance for spacecraft and mission design, I have not attempted to present as exhaustive a survey as would be found in more thorough review articles such as those recently prepared by McKibben (1987) or Quenby (1984). I have further restricted the scope of this review to nuclei below a few GeV/nucleon, which are the most significant from the point of view of producing single event upsets or latchups in circuit devices, and, with a few exceptions, to the period 1975 to 1987, which includes one complete 11 year cycle of solar activity. This is a period in which measurements were available from a number of spacecraft at significant distances (several AU) from the orbit of earth, so that the effects on the values of gradients of systematic errors in the intensity measurements at the various spacecraft is minimized.

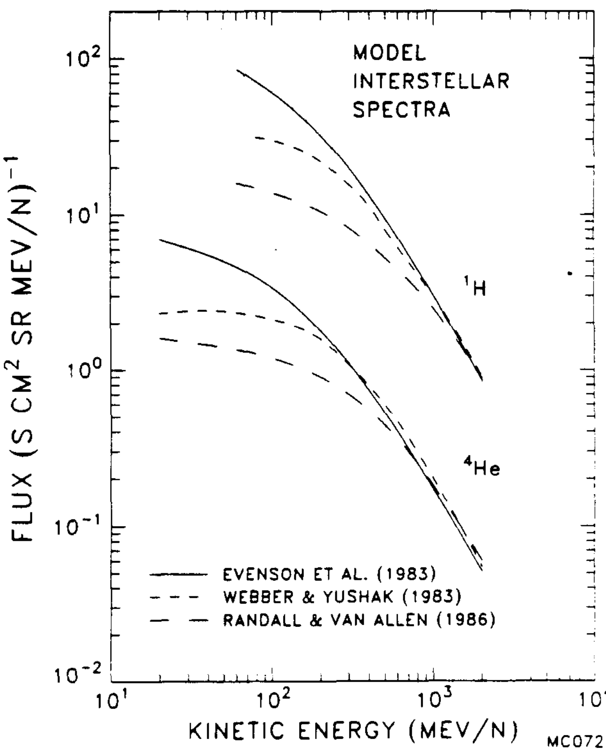

Figure 2. Estimated interstellar cosmic ray proton and helium spectra

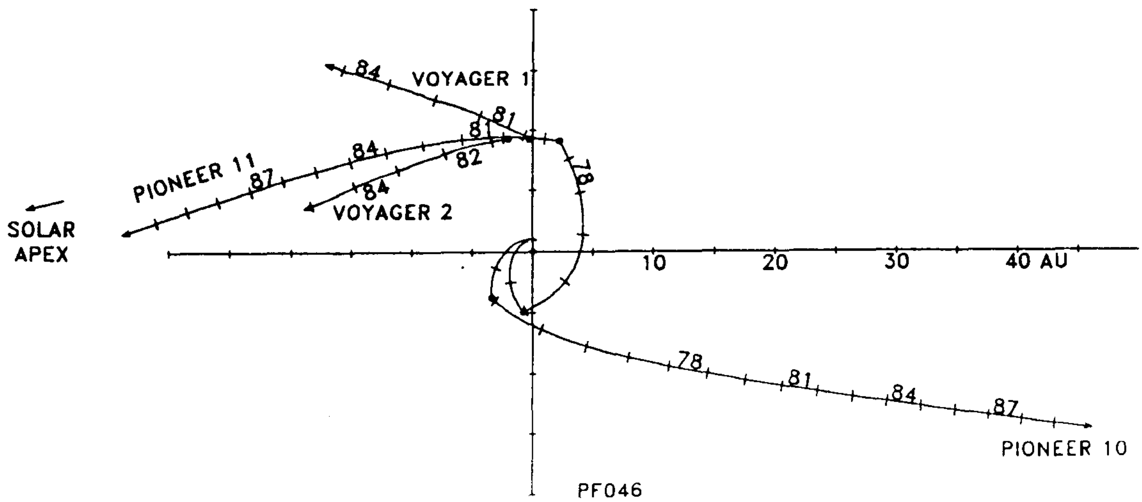

Figure 3. Pioneer 10/11 and Voyager 1/2 trajectories projected on the ecliptic.

THEORETICAL EXPECTATIONS

The theory of galactic cosmic ray modulation is well developed. The governing equations were first written down by E.N. Parker (1965) and have not been fundamentally modified since. However, the critical parameters which govern the modulated intensity remain poorly known. These parameters include, for example, the size of the modulation region and the values, spatial, and energy dependences of the components of the interplanetary diffusion tensor. As a result, the use of the equations has been more explanatory than predictive, and theoretical arguments concerning the relative importance of the terms describing the physical processes of modulation remain unsettled.

Historically, most analysis of galactic cosmic ray modulation and of spatial intensity gradients has been performed in the context of a quasi-steady, spherically symmetric modulation model. For such a model, latitude gradients, by definition, do not exist, and the predictions for the radial gradient G_r are particularly simple, being given at any point in the heliosphere by

$$G_r(r,T) = C(T)V_{SW}/\kappa(r,T) \tag{2}$$

where κ is the effective radial interplanetary diffusion coefficient at radius r, V_{SW} is the solar wind velocity, and C(T) is the Compton-Getting factor at kinetic energy T MeV/nucleon. C(T) in turn is given by

$$C(T) = (2-\alpha\gamma)/3 \tag{3}$$

where γ is the power law spectral index of the cosmic ray spectrum for the particles of interest at energy T, $\alpha = (T+2mc^2)/(T+mc^2)$, and mc^2 is the nucleon rest energy. Since below ~100 MeV/n, the modulated galactic cosmic ray spectra take the form $dJ/dT \propto T^{+1}$, $C(T) \equiv 0$ at these low energies, and gradients are expected to be small. For anomalous components, $\gamma < +1$, so that gradients for these species should be larger, as is observed. $\gamma<+1$ for higher energy galactic cosmic rays as well, so that larger gradients might be expected. However, at higher energies, κ is larger than at low energies, so that the gradients remain small.

Although equation (2) offers useful guidance as to the systematics of the dependence of radial gradients on particle energy through knowledge of the spectral form, in practice the diffusion coefficient, κ, is so poorly known as a function of position and energy that useful numerical predictions for the value of G_r can not be obtained. Furthermore, equation (2) is based on a greatly oversimplified model of modulation. More realistic models incorporate time dependence (e.g. O'Gallagher and Mazlyar, 1976; Perko and Fisk, 1983), departures from spherical symmetry (e.g. Newkirk and Fisk, 1985), and the influence of gradient and curvature drifts (e.g. Jokipii, 1986; Potgieter and Moraal, 1985).

A unique feature of models for modulation which incorporate drifts is sensitivity of the modulated cosmic ray intensity to the sign of the dipole component of the solar magnetic field, which reverses near maximum solar activity approximately every 11 years. The last reversal occurred in 1980 (Webb et al., 1984). A number of qualitative and semi-quantitative predictions can be made concerning the behavior of the spectra, intensities and gradients of galactic cosmic rays and anomalous components upon reversal of the solar dipole magnetic field (e.g. Jokipii, 1986; Potgieter and Moraal, 1985). Most such predictions lie outside the scope of this report, but two that are relevant are a) that for the sign of the dipole field pertaining after 1980, radial gradients should be larger than for the period of opposite polarity (~1970-80), and b) that upon reversal of the solar dipole field gradients in latitude should at least change markedly, and in some cases change sign. As will be demonstrated below, observations do not show the predicted increase in radial gradients, but they do appear to show a reversal of latitude gradients for at least some particle species.

Unfortunately, for all of the more sophisticated (and realistic) models involving time dependence, drifts, or other effects of non-spherical symmetry, in order to obtain quantitative predictions it is necessary to make assumptions concerning heliospheric structure in regions for which little or no information exists. Furthermore, the models are in general so complex that results can be obtained only by numerical solution of specific cases. As a result, the predictions of these models, especially for regions not yet explored, are likely to undergo significant changes as we learn more about the structure of the helisophere.

OBSERVATIONS

RADIAL GRADIENTS OF THE INTEGRAL INTENSITY ($E \gtrsim 100$ MeV/n)

The most frequently reported measurement of a gradient for the galactic cosmic ray intensity is for the integral intensity above a threshold energy, usually of the order of ~100 MeV/n. Because most of the cosmic ray intensity is at energies well above 100 MeV/n, for the modulated cosmic ray spectrum the mean energy of particles contributing to the integral intensity is of the order of 2 GeV. The gradient measurements are of two types, based either on counting rates from a single, shielded detector which responds to all particles with sufficient energy to penetrate the shielding, or on coincidence counting rates from multidetector cosmic ray telescopes which respond to particles with sufficient energy to penetrate the complete stack of detectors in the telescope. The latter generally provide a higher quality measurement since the requirement for mutiple detector firings suppresses many forms of background, and since pulse height analysis is usually available from one or more detectors in the telescope to allow the particles contributing to the counting rate to be identified, background contributions to be estimated, and gains and discriminator settings to be monitored. Furthermore, especially for experiments on the Voyager and Pioneer spacecraft, the RTG power sources provide a gamma ray backgound that grows with time. Gradient analyses based on single detector counting rates must take great pains to avoid confusing the effects of the increasing background with the effects of a radial gradient (see, for example, Van Allen and Randall, 1985, for a thorough discussion of this problem).

In Figure 4 we show as a function of time measurements of the radial gradient of the integral intensity reported by the University of Chicago using cosmic ray telescopes on board Pioneer 10 and various IMP spacecraft at 1 AU. Figure 4A shows the 27 day averages of the intensity, I, measured at the two observing points, and Figure 4B shows the radial gradient, G_r, calculated as

$$G_r = \frac{\ln[\, I(P10)/I(IMP)]}{[R(10)-1]} \tag{4}$$

where R(10) is the radial position of Pioneer 10. In order to minimize the effect of propagating disturbances in the solar wind on the gradient, it has become customary to compare Pioneer and IMP counting rates at times shifted by the propagation time for the solar wind from 1 AU to the position of Pioneer 10. This procedure has the effect of removing some of the larger temporal fluctuations in the measured gradient, but has little effect on the long-term average value of the gradient.

From Figure 4, it is clear that temporal fluctuations of the intensity in response to variations in solar activity have been comparable to the total effect of the radial gradient on the Pioneer intensity up to the present time. Therefore, it is possible to measure gradients only by comparison of well matched counting rates at two locations. It is also clear that the value of the gradient itself varies in response to the solar activity cycle. The largest average gradient, amounting to ~4%/AU, was observed early in the Pioneer 10 mission during a period of extended near-solar-minimum conditions. This large value was confirmed by Pioneer 11 measurements, and by a similar measurement from the GSFC/UNH telescope, also on Pioneer 10. The largest value observed subsequently was ~3%/AU near solar maximum in 1981-83.

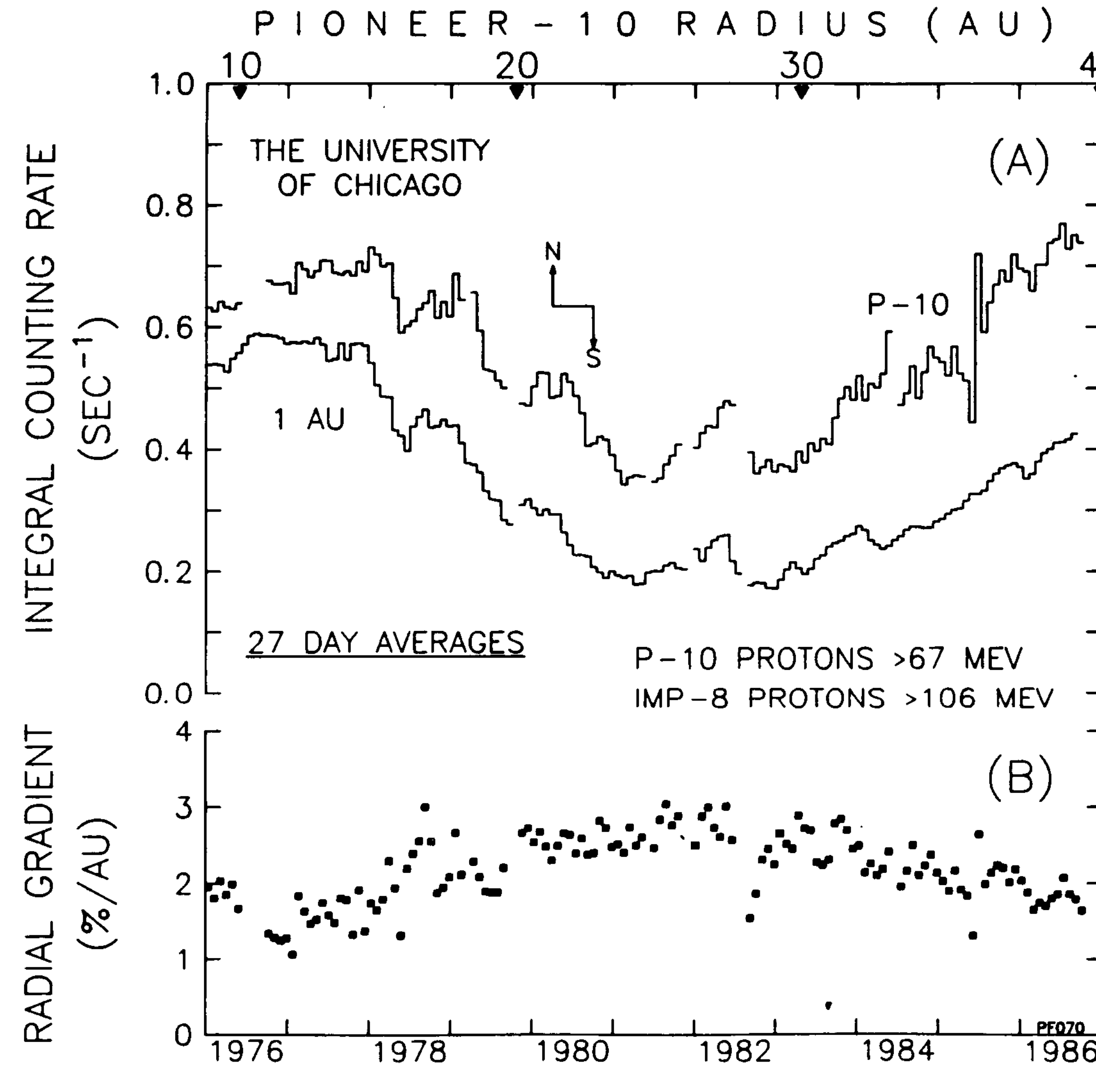

Figure 4. Integral intensities and radial gradients from Pioneer 10 and IMP 8. Reversal of the solar magnetic polarity is indicated in 1980.

For comparison, values of the integral gradient measured in each year for the period 1975-1986 reported by the University of Chicago and by other investigators are listed in Table 1. As values of the gradients were not generally reported on a yearly basis, the entries in the Table are in some cases fairly crude averages derived from published figures. They should be sufficiently accurate to indicate the trends of the data, but the original references should be consulted if greater accuracy is desired. The measurements of Lopate et al. (1987) and of Webber and Lockwood (1987) make use of coincidence counting rates from multi-detector telescopes. The other measurements are based on single detector counting rates. The agreement between the measurements is in general reasonably good, and it is clear that the value of the integral gradient is no larger than a few per cent per AU.

Note that at the time of the reversal of the solar dipole field in 1980, no significant changes in the gradient were observed, and that the value of ~1.5-2%/AU observed in the present near-solar-minimum conditions is <u>not</u> larger than that observed in the previous solar minimum. Both observations are inconsistent with the predictions of drift-dominated modulation models.

Table 1. Integral Radial Gradients (E>100MeV)
(Per cent/AU)

	Lopate et al. (1987)	Webber & Lockwood (1987)	Van Allen & Randall (1985)	Fillius† et al. (1985)	Venkatesan et al. (1986)	Max. Radius (AU)	
	P-10 IMP-8	P-10,11 VGR-1,2 IMP-8	P-10,11	P-10,11	VGR-2 IMP-8	VGR-2	P-10
1975			2.06±0.2*	1.4±0.2			8.9
1976	1.6±0.4	-----	"	1.5±0.3			11.7
1977	1.6±0.3	2.77±0.35	"	1.5±0.3		1.8	14.7
1978	2.1±0.4	2.81±0.37	"	1.9±0.1		4.7	17.5
1979	2.3±0.4	-----	"	1.9±0.2		6.1	20.5
1980	2.5±0.2	3.16±0.31	"	1.8±0.1		7.8	23.3
1981	2.7±0.3	3.15±0.30	"	1.7±0.1	3.7±0.3	9.7	26.2
1982	2.7±0.3	-----	"	1.5±0.3	3.0±1.0	10.7	28.5
1983	2.5±0.3	2.19±0.20	"	1.3±0.2	2.8±0.7	13.0	31.7
1984	2.2±0.2	1.78±0.12	"	1.1±0.1	2.3±0.7	15.9	34.5
1985	2.0±0.2	1.77±0.25	"			18.6	37.2
1986	1.8±0.2					21.0	40.0

† M1 detector, yearly values estimated from Fig. 3 of reference.
* Mean value only quoted for 1972-1985.
Variations in range 0-4%/AU reported but not identified as to time of occurrence.

The temporal variations in the value of the gradient are not well understood, and thus future behavior of the gradient cannot be confidently predicted. Also, there is no compelling evidence for changes in the value of the gradient as a function of radius. Therefore, for guidance in design, a conservative approach would be to assume no radial dependence and adopt a value of 4%/AU, equal to the largest persistent gradient measured since 1972. An upper limit on the intensity that can be reached is set by the interstellar spectrum. For the spectrum of Evenson et al. (1983) this corresponds to a flux of ~1.6 (sec cm^2 sr)$^{-1}$ above 100 MeV/n. Starting from the intensity measured at Pioneer 10 at 40 AU in 1987, with a radial gradient of 4%/AU the interstellar intensity would be reached at a radius of ~65-70 AU, whereas with the measured ~2%/AU gradient the interstellar intensity would be attained at a radius of ~90-100 AU.

3.2 RADIAL GRADIENTS IN DIFFERENTIAL ENERGY WINDOWS

Less frequently reported, but more useful for tests of modulation theory, are gradients of the intensity of particles identified as to particle species and energy. Measurement of such "differential gradients" requires use of cosmic ray telescopes in which particles can be brought to rest, or at least significantly slowed, and thus identified by charge and energy per nucleon. As for the integral gradients, it is important to compare measurements at 1 AU and at larger radii that are well matched in terms of energy and particle species. Such measurements are at present available only from the University of Chicago and GSFC/UNH telescopes on Pioneer 10 and 11 (and IMP 8) and from the CRS telescopes on Voyager 1 and 2.

In Figure 5 we show a sample of data for 2 energy ranges each for protons and helium from the University of Chicago telescopes on Pioneer 10 and IMP 8, taken from Lopate et al. (1987). The lower half of each panel contains simultaneous intensity measurements from each spacecraft for the given species and energy range, while the upper half contains the radial

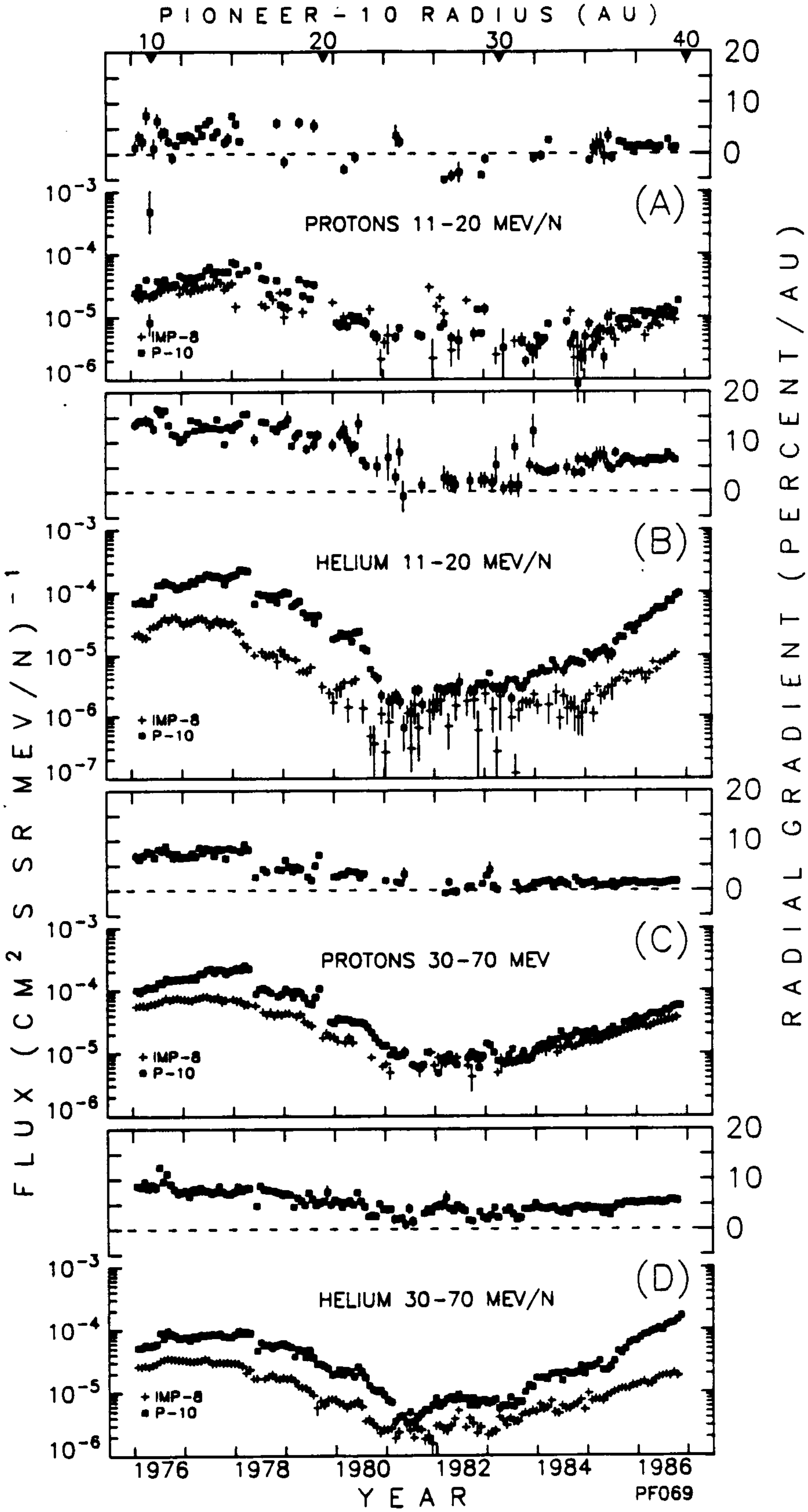

Figure 5. Fluxes and radial gradients for protons and helium in differential energy windows.

gradient computed, as for the integral gradients, by comparing propagation-shifted measurements from Pioneer 10 and IMP. The protons represent a pure galactic component, whereas the helium energy ranges contain a strong admixture of the anomalous helium component except for the period near maximum solar modulation. The radial position of Pioneer 10 is indicated along the top axis. Sample snapshots of the radial dependence of the intensity taken from the same data set at yearly intervals are shown in Figure 6, together with the estimated interstellar intensity for galactic cosmic rays of the same energy and charge, based on the interstellar spectra of Evenson et al. (1983). For the helium, which contains the anomalous component, the estimated interstellar density shown is most likely much smaller than the intensity of the anomalous component near the boundary. The upper limit to the intensity of anomalous components at the boundary is set by the energy density of the solar wind and interplanetary magnetic field at the boundary.

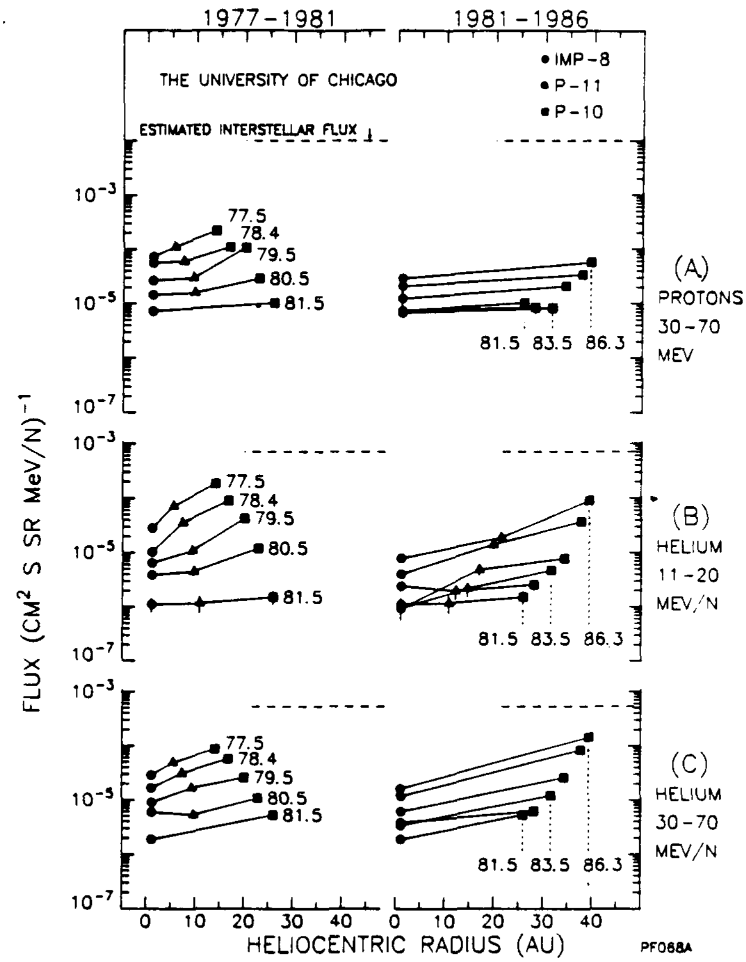

Figure 6. Yearly snapshots of low energy proton and helium flux vs. radius.

In all four panels of Figure 5, the magnitude of temporal variations in response to the solar activity cycle exceeds the magnitude of the effects due to the radial gradient between 1 and 40 AU. Thus, once again, comparison of measurements at two different radii is required for measurement of a gradient. Furthermore, the gradients themselves exhibit strong time dependence. Most striking is the near disappearance of the radial gradient for low energy galactic protons during the period of maximum solar modulation, and the strong reduction in the value of the gradient for the mixed anomalous and galactic helium. Such an effect was not anticipated from available modulation models. The reduction of the helium gradient appears to coincide with the disappearance of the anomalous helium spectrum at Pioneer 10 and with the reversal of the solar dipole polarity, both of which occurred in 1980. As is discussed elsewhere in these proceedings (Cummings, 1987; Jokipii, 1987; Mewaldt et al, 1987), models of modulation incorporating drifts provide reason to expect significant changes in the anomalous component spectra upon reversal of the solar magnetic polarity. However, they do not predict disappearance of the radial gradient. Furthermore, in contradiction to the observations, such models in general predict that in the approach to the new solar minimum in 1987, radial gradients should be larger than in the solar minimum of the 1970's.

Other measurements for differential radial gradients for these and for other energy intervals and species have been reported by McDonald et al. (1986) for protons and helium in energy intervals up to 380 MeV/nucleon, and for anomalous oxygen by Lopate et al. (1987) and Cummings et al. (1987a, b). Table 2 contains a selection of these observations for the years

Table 2. Differential Radial Gradients

Species	Energy Range (MeV/n)	Measured Gradients (Per cent/AU) 1977	1982	1986	Reference
Protons	11-20	4.2±1.6	-3.7±1.6*	1.5±0.5	A
Protons	29-67	7.7±0.8	0.7±1.2	1.5±0.2	A
	30-55	8±3**	2.5±1.5**	2.5±1.5**	B
Protons	140-240	6.5±5.5**	3±3*?	3.5±0.5	B
Helium†	11-20	12.2±0.2	-1.5±2.4	5.9±0.6	A
	10-21	17±5**	3±1**	5.0±0.5	B
Helium†	29-67	7.6±0.6	3.6±1.4	5.5±0.2	A
	30-55	10±5**	3.0±0.5**	5.7±1.3**	B
Helium	150-380	4.5±2.5**	4.0±0.5**	3±1**	B
Carbon	21-37	---	----	~2	A
Oxygen†	5.4-8.5	---	----	15.5±2.1	C
	8.5-13.9	---	----	15.3±2.0	C
	13.9-30.6	---	----	12.3±2.3	C
	24-43	---	----	~8	A

Notes
* Possible Solar Contamination
** Corresponds to range of values quoted.
† Contains anomalous component

References
A) Lopate et al. (1987)
B) McDonald et al. (1986)
C) Cummings et al. (1987b)

1977, 1982, and 1986, corresponding to periods before, during, and after the most recent maximum in the 11 year solar modulation cycle. Agreement between the various measurements is in general excellent.

If the observed gradients for galactic cosmic rays are extended in radius, the radius at which the estimated interstellar intensity is attained varies strongly with the phase of the solar cycle. For example, for 1977 and before, the 29-67 MeV proton observations suggest that the boundary would be reached near 50 AU, but in 1986, the observed gradient suggests that the boundary lies near 300 AU. These numbers should not be taken seriously, however, for it is likely that the radial gradient depends strongly on radius in some region near the boundary. There are some indications of a radial dependence for the radial gradients in observations made between Pioneer 10, Voyager 2, and 1 AU and reported by McDonald et al. (1986), but it is so far difficult to organize the observed variations into a systematic model that might allow general conclusions and predictions to be made concerning radial dependence of the gradients.

The observational situation for differential gradients may be summarized by the statement that radial gradients for galactic cosmic rays at low energy ($E \lesssim 100$ MeV/n) are always small ($\lesssim 10$%/AU) and positive. Gradients for anomalous component species are somewhat larger, of the order of 15%/AU, independent of species. Gradients of galactic cosmic rays show temporal variations associated with changes in the level of solar activity, but these changes are not well understood in terms of current models. Therefore, it is not possible to predict with any confidence the behavior of the gradients in future phases of the solar activity cycle.

GRADIENTS IN HELIOSPHERIC LATITUDE

Recently, measurement of gradients in heliospheric latitude has become a very active area of research. In part this is because current modulation models tend to emphasize the importance of conditions at moderate and high latitudes for determining the modulated intensity near the ecliptic, and in part this is because two spacecraft, Voyager 1 and Pioneer 11, are significantly above the ecliptic, at ~30° and 17° latitude, respectively, so that direct measurements of latitude gradients are possible.

Ground based or earth-orbit observations have also been used to measure gradients in latitude with respect to the heliospheric "equatorial" current sheet which separates positive and negative magnetic polarity in the solar wind, and which drift-dominated models of modulation suggest may be the crucial symmetry plane for modulation of cosmic rays. Since the current sheet usually has a large inclination to the ecliptic, an observer at earth may sample a large range in magnetic latitude in the course of one solar rotation. For integral intensity measurements made with neutron monitors (mean energy ≡ a few GeV), Newkirk and Fisk (1985), and Newkirk et al. (1985, 1986) have performed an extensive study of gradients with respect to the current sheet, using K-coronameter observations to infer the inclination of the sheet. Newkirk et al. (1986) have also extended the measurement of latitude gradients to lower energies by applying the same techniques they used for the integral measurement to spacecraft observations. For the integral flux, for the years 1973-77, and, in preliminary work, 1984, they find a persistent average negative gradient of ~2.7%/AU (~0.05%/degree) at 1 AU to latitudes of ±30°. They further find that the magnitude of the gradient depends upon rigidity approximately as $P^{-\alpha}$ where α is in the range $0.72 < \alpha < 0.86$. Drift-dominated models of modulation predict that near the current sheet, the average latitudinal gradient should be negative for all phases of the solar cycle, and the observed magnitude is consistent with the choice of reasonable parameters in such models (e.g. Jokipii and Kota, 1986). However, a significant change in magnitude should have been expected after 1980, which, at least in the preliminary analysis of the observations, does not seem to have occurred.

Using direct measurements of the integral intensity from Voyager 1 at high latitude and Voyager 2 near the ecliptic, Christon et al. (1985, 1986a) have used a complex multi-parameter analysis to deduce the existence of a negative gradient of ~2%/AU (~0.5%/degree) away from the current sheet near a radius of 15 AU in 1981-83. In data obtained from these spacecraft after mid-1985, clear evidence for a latitude gradient appears even without sophisticated analysis, since the intensity measured by both integral and differential energy channels on Voyager 1 at latitudes >25° has been lower than that at Voyager 2 near the ecliptic, despite the fact that Voyager 1 is about 6 AU further from the sun than Voyager 2, and that radial gradients measured between spacecraft in the ecliptic continued to be positive outwards (Christon et al., 1986b; McDonald and Lal, 1986; Cummings et al., 1987a, b). Appearance of these large and unambiguous latitude gradients appears to have been associated with a decrease in the inclination of the current sheet to below the latitude of Voyager 1 (e.g. Christon et al., 1986b).

For galactic cosmic rays, the gradients in latitude are reported to be of order 0.5%/degree, with little dependence on particle rigidity (McDonald and Lal, 1986). For anomalous components, the gradients appear to be much larger, of order 3-4%/degree and 1-2% degree for anomalous oxygen and anomalous helium, respectively, in late 1985 - early 1986 (Cummings et al., 1987a) and 3-6%/degree for both species later in 1986 at radii near 28 AU (Cummings et al., 1987b). In terms of models of modulation, it is possible to interpret these results using either drift-dominated or drift-free models of modulation, in the latter case appealing to an observed positive gradient in solar wind velocity away from the current sheet (Newkirk and Fisk, 1985). Drift-free models would predict a negative gradient for both signs of the solar magnetic polarity, whereas drift-dominated models might predict a reversal in sign of the gradient upon reversal of the polarity, depending on the particle species and energy and the latitude range sampled.

Prior to the recent Voyager observations, the only positive reported measurement of a latitude gradient is that performed with Pioneer 11 in 1975-76, when the spacecraft rose to a heliographic latitude of 16° at a radius of ~4 AU (Bastian et al., 1979; McKibben et al, 1979). In these observations, evidence for a latitude gradient of ~2-3%/degree positive away from the ecliptic plane was reported. The correlation between intensity and latitude was significant to >4σ, but temporal variations could not be excluded absolutely as a source for the effect. Nevertheless, the existence of a positive latitude gradient for the anomalous helium provided the simplest interpretation of the observations. No statistically significant latitude gradients were found for galactic cosmic ray protons or for the integral intensity of galactic cosmic rays.

If the interpretation of the Pioneer 11 observations as a latitude gradient is correct, then these observations show a reversal of the latitude gradient, at least for the anomalous helium, in two successive solar activity cycles, consistent with predictions of drift-dominated models. Thus, it may be expected that following the field reversal anticipated in ~1991, latitude gradients for anomalous components may again be positive away from the ecliptic. It is risky to extend this conclusion to galactic cosmic rays, however, for the anomalous components most likely are accelerated in a localized region within the heliosphere, whereas galactic cosmic rays are incident uniformly and isotropically on the boundary of the modulation region. Thus, the effects of modulation on the galactic and anomalous component cosmic rays differ significantly. Indeed the only experimental reports of latitude gradients for galactic cosmic rays prior to the 1980 field reversal suggest no change in the sign of the latitude gradient (Fisk and Newkirk, 1985;, Newkirk et al., 1985, 1986).

In summary, the most solid evidence for the existence of latitude gradients to date is that provided by Voyager 1/2 observations for the period after 1985. The gradients are larger for anomalous components (~3-6%/degree) than for galactic cosmic rays (~0.5%/degree), and are relatively independent of rigidity for galactic cosmic rays. For the anomalous helium, a previous measurement by Pioneer 11 in 1975-76 suggests that the sign of the latitude gradient reversed between 1976 and 1985. No such conclusion is warranted at present for galactic cosmic rays. Extension of these observations to latitudes higher than the 30° attained by Voyager 1 would be very uncertain.

SUMMARY

At the present time, experimental knowledge of cosmic ray radial and latitudinal gradients covers the region from 0.3 to 40 AU, and latitudes from the ecliptic northward to 30°. In this region, the radial gradients are small (<10%/AU for galactic cosmic rays of all energies, ~15%/AU for anomalous components) and variable in time. Latitude gradients for anomalous components are of the order of 3 - 6 %/degree and appear to be sensitive to the polarity of the solar dipole magnetic field, being negative for the current polarity, and positive for the polarity of the last solar cycle (~1970-1980). Latitude gradients for galactic cosmic rays are smaller (~0.5%/degree), and have only recently been measured for the first time, so that their sensitivity to the solar magnetic polarity is unknown. While the values observed are consistent with currently available theoretical models, neither the time variability nor the values of the gradients could have been reliably predicted from the models. The location of the boundary of the modulation region remains unknown, and extrapolation of the measured gradients to larger (or smaller) radii, to higher latitudes, or to later times is difficult to do with confidence. If such extrapolation is required, recommended values for radial and latitude gradients based on currently available observations are given by Mewaldt et al. (1987), who have summarized the findings of this workshop.

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